POLICY FORUM

ENERGY

Sustainable minerals and metals for a low-carbon future

Policy coordination is needed for global supply chains

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Climate change mitigation will create new natural resource and supply chain opportunities and dilemmas, because substantial amounts of raw materials will be required to build new low-carbon energy devices and infrastructure (*1*). However, despite attempts at improved governance and better corporate management, procurement of many mineral and metal resources occurs in areas generally acknowledged for mismanagement, remains environmentally capricious, and, in some cases, is a source of conflict at the sites of resource extraction (*2*). These extractive and smelting industries have thus left a legacy in many parts of the world of environmental degradation, adverse impacts to public health, marginalized communities and workers, and biodiversity damage. We identify key sustainability challenges with practices used in industries that will supply the metals and minerals—including cobalt, copper, lithium, cadmium, and rare earth elements (REEs)—needed for technologies such as solar photovoltaics, batteries, electric vehicle (EV) motors, wind turbines, fuel cells, and nuclear reactors. We then propose four holistic recommendations to make mining and metal processing more sustainable and just and to make the mining and extractive industries more efficient and resilient.

Between 2015 and 2050, the global EV stock needs to jump from 1.2 million light-duty passenger cars to 965 million passenger cars, battery storage capacity needs to climb from 0.5 gigawatt-hour (GWh) to 12,380 GWh, and the amount of installed solar photovoltaic capacity must rise from 223 GW to more than 7100 GW (*3*). The materials and metals demanded by a low-carbon economy will be immense (*4*). One recent assessment concluded that expected demand for 14 metals—such as copper, cobalt, nickel, and lithium—central to the manufacturing of renewable energy, EV, fuel cell, and storage technologies will grow substantially in the next few decades (*5*). Another study projected increases in demand for materials between 2015 and 2060 of 87,000% for EV batteries, 1000% for wind power, and 3000% for solar cells and photovoltaics (*6*). Although they are only projections and subject to uncertainty, the World Bank put it concisely that "the clean energy transition will be significantly mineral intensive" (*7*) (see the figure).

Many of the minerals and metals needed for low-carbon technologies are considered "critical raw materials" or "technologically critical elements," terms meant to capture the fact that they are not only of strategic or economic importance but also at higher risk of supply shortage or price volatility (*8*). But their mining can produce grave social risks. A majority of the world's cobalt, used in the most common battery chemistries for EVs and stationary electricity storage, is mined in the Democratic Republic of Congo (DRC) (see the map), a country struggling to recover from years of armed conflict. There, women and sometimes children often work in or around mines for less pay or status than their male and adult counterparts, without basic safety equipment (see the photo). Owing to a lack of preventative strategies and measures such as drilling with water and proper exhaust ventilation, many cobalt miners have extremely high levels of toxic metals in their body and are at risk of developing respiratory illness, heart disease, or cancer.

In addition, mining frequently results in severe environmental impacts and community dislocation. Moreover, metal production itself is energy intensive and difficult to decarbonize. Mining for copper, needed for electric wires and circuits and thin-film solar cells, and mining for lithium, used in batteries, has been criticized in Chile for depleting local groundwater resources across the Atacama Desert, destroying fragile ecosystems, and converting meadows and lagoons into salt flats. The extraction, crushing, refining, and processing of cadmium, a by-product of zinc mining, into compounds for rechargeable nickel cadmium batteries and thin-film photovoltaic modules that use cadmium telluride (CdTe) or cadmium sulfide semiconductors can pose risks such as groundwater or food contamination or worker exposure to hazardous chemicals, especially in the supply chains where elemental cadmium exposures are greatest. REEs, such as neodymium and the less common dysprosium, are needed for magnets in electric generators in wind turbines and motors in EVs, control rods for nuclear reactors, and the fluid catalysts for shale gas fracking. But REE extraction in China has resulted in chemical pollution from ammonium sulfate and ammonium chloride and tailings pollution that now threaten rural groundwater aquifers as well as rivers and streams. Several metals for green technologies are found as "companions" to other ores with differential value and unsustainable supply chains (*9*).

POLICY RECOMMENDATIONS

With these sobering social and environmental aspects of current mineral extraction in mind, we suggest four policy recommendations.

Diversify mining enterprises for local ownership and livelihood dividends

Although large-scale mining is often economically efficient, it has limited employment potential, only set to worsen with the recent arrival of fully automated mines. Mining can concentrate occupational hazards as well as environmental risk, as demonstrated most severely by tailings pond disasters and mining wastewater contamination. Even where there is relative political stability and stricter regulatory regimes in place, there can still be serious environmental failures, as exemplified by the recent global rise in dam failures at settling ponds for mine tailings. The level of distrust of extractive industries has even led to countrywide moratoria on all new mining projects, such as in El Salvador and the Philippines.

Traditional labor-intensive mechanisms of mining that are possible to undertake with less mechanization and without major capital investments are called artisanal and small-scale mining (ASM). Although ASM is not immune from poor governance or environmental harm, it provides livelihood potential for at least 40 million people worldwide, with an additional three to five times more people indirectly supported by the sector (*10*). It is also usually more strongly embedded in local and national economies than foreign-owned, large-scale mining, with a greater level of

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value retained and distributed within the country. Diversifying mineral supply chains to allow for greater coexistence of small- and large-scale operations is needed. Yet, efforts to incorporate artisanal miners into the formal economy have often resulted in a scarcity of permits awarded, exorbitant costs for miners to legalize their operations, and extremely lengthy and bureaucratic processes for registration.

Development donors need to focus on bottom-up formalization efforts rather than merely facilitating government efforts to better regulate the sector for increased tax revenues. There needs to be a focus on policies that recognize its livelihood potential in areas of extreme poverty. Moreover, formalization of the sector should focus on creating stronger, more accountable arrangements to drive greater value of resource revenues down the supply chain to ASM miners to ensure better environmental and safety mechanisms and expand their access to markets. The recent decision of the London Metals Exchange to have a policy of "nondiscrimination" toward ASM is a positive sign in this regard. Certain industry actors have demonstrated a commitment to, and the benefits of, this type of approach, such as Fairphone's sourcing of the mineral columbite-tantalite (coltan) used in mobile phones. At the level of government policy, ASM has demonstrated its ability to increase productivity and mechanize production, even in hostile regulatory and governance environments. More space for and support to ASM to pursue this trajectory would enhance its capacity to meet the increased demand for minerals required in the move toward a low-carbon future. One place to begin is with the redistribution of dormant mining concessions previously granted to (but unused by) mining companies so that local ASM operators can legally work in these locations, as has been taking place recently in Tanzania.

A creuseur, or digger, descends into a Congolese copper and cobalt mine in Kawama. Wages are low, and working conditions are dangerous, often with no safety equipment or structural support for the tunnels.

PHOTO: MICHAEL ROBINSON CHAVEZ/*THE WASHINGTON POST* VIA GETTY IMAGES

Acknowledge the limits of traceability

A great deal of attention has focused on fostering transparency and accountability of mineral mining by means of voluntary traceability or even "ethical minerals" schemes. International groups, including Amnesty International, the United Nations, and the Organisation for Economic Co-operation and Development, have all called on mining companies to ensure that supply chains are not sourced from mines that involve illegal labor and/or child labor. In concert, Eurasian Resources Group (ERG) launched their Clean Cobalt Framework in 2018, First Cobalt has their Responsible Cobalt Initiative, RCS Global has its Better Cobalt program, Amnesty International is working on an Ethical Battery framework, and the World Economic Forum launched a Global Battery Alliance committed to "responsible sourcing" of raw materials for batteries.

Traceability schemes, however, may be impossible to fully enforce in practice and could, in the extreme, merely become an exercise in public relations rather than improved governance and outcomes for miners. In the eastern DRC, for example, cassiterite, the mineral that tin is extracted from, is exported through a traceability system yet can nonetheless have contributed to conflict financing or labor and human rights abuses while simultaneously introducing heavy financial costs onto local workers for the right to participate in the system (*11*). Nonetheless, traceability is not without promise, and examples from Blockchain technology show how the use of artificial intelligence algorithms for data processing has the potential for greater assurance but ultimately relies on the accuracy of data being fed into the supply chain.

Transparency of supply chains is a means to an end and will only be effective if consumers or regulators start to differentiate between products being provided. There are effective lessons on traceability and transparency arising from the Kimberley Process for conflict diamonds; the Extractive Industries Transparency Initiative for oil, gas, and mineral resources; and the Fairmined Standard for gold that could be applied to the mineral supply chains needed for decarbonization. Paramount among these is an acknowledgment that traceability schemes offer a largely technical solution to profoundly political problems and that these political issues cannot be circumvented or ignored if meaningful solutions for workers are to be found. Traceability schemes ultimately will have value if the market and consumers trust their authenticity and there are few potential opportunities for leakage in the system.

Explore new resource streams

Although primary emphasis must be placed on resource efficiency (higher output or usage of product per unit of resource input) and recycling, there will likely be a need for primary resource extraction as well owing to clean-energy infrastructure demand. New resource streams—including metal availability in seawater (desalination) and groundwater (geothermal brines), material substitution or material intensity reductions, and materials recovery and recycling—also hold promise for diversifying supply chains, as long as they maintain environmental sustainability and protect worker safety.

Although mining in terrestrial areas is likely to continue to meet the demands of low-carbon technologies in the nearer term, we need to carefully consider mineral sources beneath the oceans in the longer term. The

International Seabed Authority, set up under the United Nations (UN) Convention on the Law of the Sea, is in the process of issuing regulations related to oceanic mineral extraction. This process is a rare opportunity to be proactive in setting forth science-based environmental safeguards for mineral extraction. For metals such as cobalt and nickel, ocean minerals hold important prospects on the continental shelf within states' exclusive economic zones as well as the outer continental shelf regions. Within international waters, metallic nodules found in the vast Clarion-Clipperton Zone of the Pacific as well as in cobalt and tellurium crusts, which are found in seamounts worldwide, provide some of the richest deposits of metals for green technologies. Difficult extraction and declining reserves of some terrestrial minerals, as well as social resistance against terrestrial mining, may lead to oceanic mineral reserves becoming more plausible sources. Minerals near hydrothermal vents are in more pristine and distinctive ecosystems and should likely remain off-limits for mineral extraction for the foreseeable future.

Technological substitution can play an important role as well. Copper offers an illustrative example. Higher copper prices in recent years have incentivized replacement in new applications in the automotive industry, such as wire harnesses and replacing copper with aluminum winding in motors. However, substitution to other primary metals or even synthetics could merely shift resource demand to another material that may be more abundant initially but can become more challenging to procure over time. Moreover, substitution may be limited to particular innovations or niches. Alternatives to lithium-ion batteries, such as sodium-ion batteries, are becoming more practical and feasible. But finding substitutes for metals like platinum group metals in key technologies such as fuel cells has become increasingly difficult, and reserves are dwindling.

Recycling and better resource efficiency can play a part at extending and enhancing the lifetimes of products and also stretching out mineral reserves. Closed-loop supply chains based on circular economy ideas in addition to advancements in metallurgy, reverse logistics, waste separation, materials science, waste processing, and advanced recycling can all enhance the longevity and continual reuse of minerals and metals. Researchers at the U.S. National Renewable Energy Laboratory estimate that 65% of the U.S. domestic cobalt demand in 2040 could be supplied by end-of-life lithium-ion batteries, provided a robust take-back and recycling infrastructure is in place.

Extended producer responsibility (EPR) is a framework that stipulates that producers are responsible for the entire lifespan of a product, including at the end of its usefulness. EPR would, in particular, shift responsibility for collecting the valuable resource streams and materials inside used electronics from users or waste managers to the companies that produce the devices. EPR holds producers responsible for their products at the end of their useful life and encourages durability, extended product lifetimes, and designs that are easy to reuse, repair, or recover materials from. A successful EPR program known as PV Cycle has been in place in Europe for photovoltaics for about a decade and has helped drive a new market in used photovoltaics that has seen 30,000 metric tons of material recycled. To date, EPR has mainly shaped collection, recycling, and waste management to ensure safe and responsible disposal of specific classes of products like e-waste, paint, and pharmaceuticals, but, in concept, it is also meant to help drive more sustainable design as well as options for reuse and repair. There is evidence of EPR's influence on green design in the global solar industry. For example, thin-film manufacturer First Solar screens new materials to ensure that they will not negatively influence their recycling process, through which they currently recover 90% of their CdTe semiconductor material and 90% of their glass. To more easily recycle the plastics and copper from photovoltaics, some manufacturers are seeking out halogen-free components.

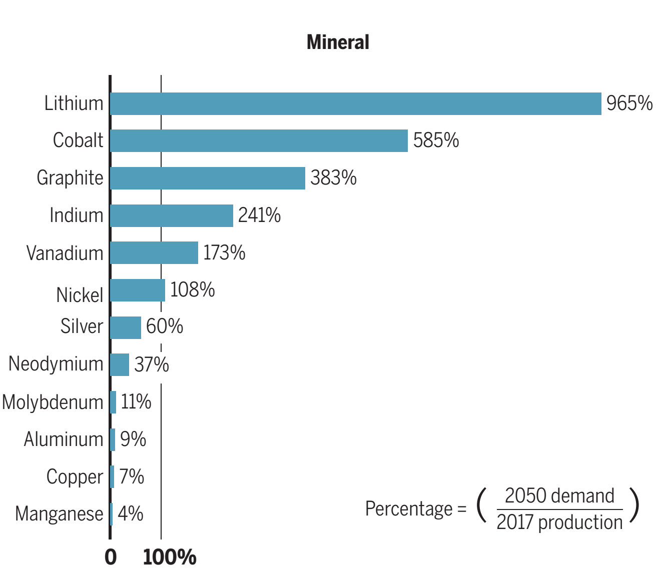
Space mining, although potentially useful for developing lunar and planetary bases farther into the future, has less potential for meeting the demand for minerals for immediate decarbonization on Earth. A possible exception to this may be platinum group metals from asteroids, but here, too, the time frame and quantity of production would preclude its use in meeting immediate technology needs for climate mitigation.

Incorporate minerals into climate and energy planning

Given the centrality of minerals and metals to the future diffusion of low-carbon technologies, materials security should be actively incorporated into formal climate planning. This could be connected to ongoing planning as part of the nationally determined contributions (NDCs) under the Paris Accord, the European Commission's National Energy and Climate Plans (NECPs), or even energy policy-making at the national scale. Climate planners could begin by mapping out their NDC contributions alongside a list of "critical minerals" for energy security (see supplementary materials).

Although care must be taken to ensure that the NDC process does not become too broad or research intensive, we believe the NDCs are the most tangible international policy consensus mechanism on this matter. The NDCs can incorporate some of the mineral sourcing challenges through efforts at resource efficiency. The Group of Seven (G7) has taken on this linkage, and policies to motivate resource efficiency can be a means of keeping track of material

Growth in mineral needs for low-carbon energy technology



Mineral	Production 2017 (kilo–metric tons)	Demand 2050 (kilo–metric tons)
Lithium	43	415
Cobalt	110	644
Graphite	1200	4590
Indium	0.72	1.73
Vanadium	80	138
Nickel	2100	2268
Silver	25	15
Neodymium	23	8.4
Molybdenum	290	33
Aluminum	60,000	5583
Copper	19,700	1378
Manganese	16,000	694

All production and demand data reflect annual values. 2017 data reflect annual production for all uses. 2050 data reflect estimated demand for only low-carbon energy technology uses. Data from (7).

GRAPHIC: X. LIU/*SCIENCE*

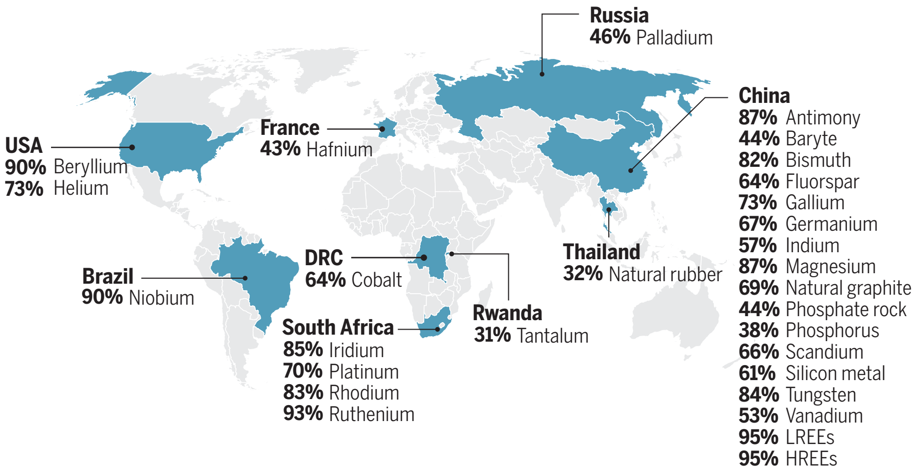
and mineral supply chains. For example, a materials assessment for particular infrastructure options for climate change mitigation or adaptation could be included in cost-benefit analyses. Recent work has suggested that the social acceptability of tying resource-efficient products to climate change mitigation efforts is strong (*12*).

Having each country create a list of critical minerals within its NDC process and show possible trade-offs and shortfalls could lead to several benefits. More efforts on national critical material analysis could result in improved mapping of mineral supply chains, for which there is already a notable gap across many developing countries and regions. The analytical efforts would enhance our understanding of supply constraints and demand patterns, which in turn could lead to a better understanding of future prices and drivers, especially those beyond the control of governments and policy as agents of change. The process of mapping mineral demands for NDCs, NECPs, and national energy policies could lead to new linkages and networks and a raising of awareness, connecting the traditional minerals and metals community to other research and social communities, especially in climate policy and energy studies. In this way, climate mitigation could be twinned with minerals security and industrial strategy as a way to meet broad sets of goals (environmental, political, and economic) in one stroke.

AN ETHICAL CONUNDRUM

Mineral and metal supplies are geologically determined, yet socially mediated. Even if supplies are enhanced through coproducts of other industries, new resource streams, and considerable expansion of recycling and increased recovery rates, there are likely to be bottlenecks across metal supply chains (*13*). This is exacerbated by poorly functioning markets, as least for the minor metals. Hence, trade policy will need to become more deftly aligned with mineral supply in ways which are both economically and ecologically more efficient. Furthermore, more robust reporting and emissions data will be required across the supply chain. For example, although the U.S. government strategy for mineral supply security released in June 2019 highlights the importance of trade with allies and partners, it does not consider where it is most ecologically efficient to source minerals. Pursuing decarbonization simultaneously with principles of a circular economy, coupled with increased market transparency mechanisms and full lifecycle reporting, could yield important social and environmental benefits.

Countries accounting for the largest share of critical raw materials



DRC, Democratic Republic of Congo; LREEs, light rare earth elements; HREEs, heavy rare earth elements. Figure modified from European Commission, "Third list of critical raw materials for the EU of 2017" (European Commission, 2017); https://ec.europa.eu/growth/sectors/raw-materials/specific-interest/critical_en.

Consideration should also be given to where mining is most likely to have a positive development footprint while also having more manageable environmental impacts (*14*). Utilizing tools such as the Responsible Mining Index and platforms such as the Responsible Minerals Initiative or the Intergovernmental Forum on Mining, Minerals, Metals and Sustainable Development may be a way forward. Although there may be treaty fatigue among policy-makers, an intertreaty protocol on mineral supply chains to ensure that the goals of existing treaties are met could enhance effective governance. Conversations in this vein should be attempted among the parties to the UN Framework Convention on Climate Change, through the UN Environment Assembly, as well as more focused mechanisms such as the U.S. government's recently launched Energy Resource Governance Initiative, the World Bank's Climate-Smart Mining Facility, or the European Institute of Innovation and Technology for Raw Materials.

Having just marked the 150th anniversary of the formulation of the periodic table, it is high time we realize that the elements, and the minerals in which they are embedded, are essential to our attainment of low-carbon goals. There is an ethical conundrum to addressing climate change only by aggravating other social and ecological problems related to unsustainable mineral and metal supply chains. But done sustainably, an impending mining boom could help lift communities out of poverty, accelerate technical innovation for decarbonization, and further the realization of energy and climate targets. Which direction it takes will depend considerably on how metal and mineral supply chains are governed over the next few critical years. ■

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